TOPSiDE

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We report on the development of a detector concept for the planned Electron-Ion Collider, TOPSiDE. The concept takes advantage of recently established, novel technologies for colliding beam detectors, such as imaging calorimetry and Ultra-Fast Silicon Detectors. The aim of the concept is to measure and identify each particle produced in *ep/eA* collisions individually. This is achieved through the use of a precision silicon tracker together with a particle-identifying, imaging calorimeter.

We will briefly review the concept, followed by a description of the detector R&D being pursued to realize TOPSiDE.

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1. Introduction: The Electron-Ion Collider and TOPSiDE

The Electron-Ion Collider (EIC) is a planned facility for the study of *ep* and *eA* collisions. Two possible sites to host the facility are being considered: Brookhaven National Laboratory and Jefferson Lab. Table I. lists the major parameters of the EIC in comparison to the ones of the first and only *ep* collider to date, HERA in Hamburg, Germany. The notable differences between the two facilities, such as the significantly higher luminosity and the polarization of the hadron beams, are highlighted in red.

	HERA	**EIC**
Operation	1992 – 2007	> 2030
Electrons/positrons	27.5 GeV (polarized)	5 – 18 GeV polarized
Protons	820 → 920 GeV not polarized	60 – 250 GeV polarized
Ions	Not available	Up to 100 GeV/u polarized
Center-of-mass energy	300 → 318 GeV	35 – 140 GeV
Luminosity	10^{32} cm^{-2} s^{-1}	$> 10^{34}$ cm^{-2} s^{-1}
Colliding beam detectors	H1, ZEUS	?
Fixed target experiments	HERMES, HERA-B	?

Table I. Comparison of the major parameters of the EIC and HERA, the first and only *ep* collider to date.

Currently, four different detector concepts [1] are being developed for the EIC: Beast (centered at Brookhaven National Laboratory), JLEIC (centered at Jefferson Lab), ePHENIX (evolving from the sPHENIX detector at RHIC), and TOPSiDE. Of these, TOPSiDE is arguably the most modern and challenging concept, one which utilizes recent progress achieved in the development new paradigms and technologies for future High-Energy Physics colliding beam detectors.

TOPSiDE aims at the measurement and identification of each particle produced in *ep* or *eA* collisions individually, thus providing a list of identified particles and their momenta similar to what is obtained at the hadron level in Monte Carlo simulations of hard interactions. This goal is realized with the combination of a precision silicon tracker and an imaging calorimeter. The identification of particles (pion-kaon-proton separation) is accomplished through measurements of the particles time-of-flight by the calorimeter itself. Thus the latter becomes a particle-identifying, imaging or 5D (dimension) calorimeter. A sketch of the TOPSiDE concept is shown in Fig. 1.

The advantages of this approach based on 5D calorimetry are many, with some of the most important ones listed in [2]. The elegance of the concept is evident from the limited number of different subsystems. In the forward (hadron) direction the detector features a Ring Imaging Čerenkov (RICH) detector, as time-of-flight measurements cannot distinguish particles above say 10 GeV/c, given the limited flight path. To provide a precision measurement of the forward particle momenta a dipole of toroidal magnet is located behind the RICH detector.
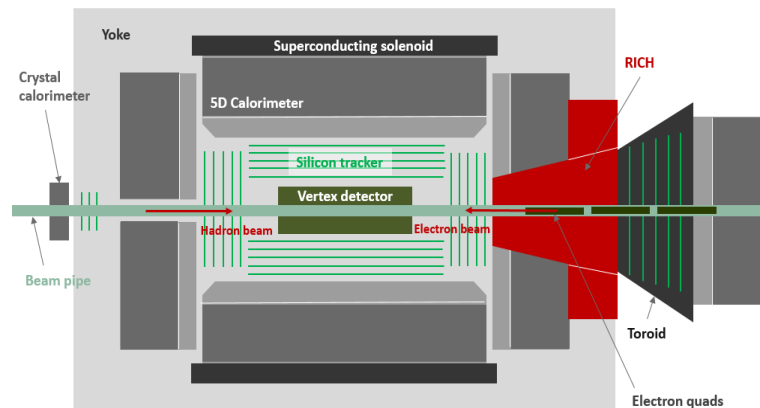

Figure 1. Sketch of the TOPSiDE detector concept.

2. Ultra-Fast Silicon Detectors

The TOPSiDE concept requires Ultra-fast Silicon Detectors (UFSDs) with excellent timing resolution. GEANT4-based Monte Carlo simulations of TOPSiDE showed that a resolution of 10 picosecond or better is needed to distinguish pions and kaons with momenta up to 7 GeV/c (at the EIC, this is the range of momenta for most of the solid angle).

UFSDs are being developed by various groups worldwide [3]. Currently, the best performance achieved a time resolution of 18 picosecond [4]. This result was obtained with 35 μm thick sensors based on the Low-Gain Avalanche Diode (LGAD) technology and read out by an external digitization system.

During the past year or so, Argonne completed the design of its own sensor [2] using the Silvaco ATLAS simulation tools [5]. The sensor is nominally 50 μm thick and features 1 x 1 mm^2 pixels. At the edge of the sensor, five guard rings reduce the leakage current and therefore increase the breakdown voltage. The operating voltage is around -200 V. All relevant parameters of its design have been studied, starting with the mapping of the electric fields and the establishment of the breakdown voltage. As an example, Fig. 2a left (right) shows the dependence of the leakage (signal) current on the operating temperature. Note that operating at say -20 ^{0}C offers two distinct advantages: a significantly reduced leakage current and an enhanced signal current.
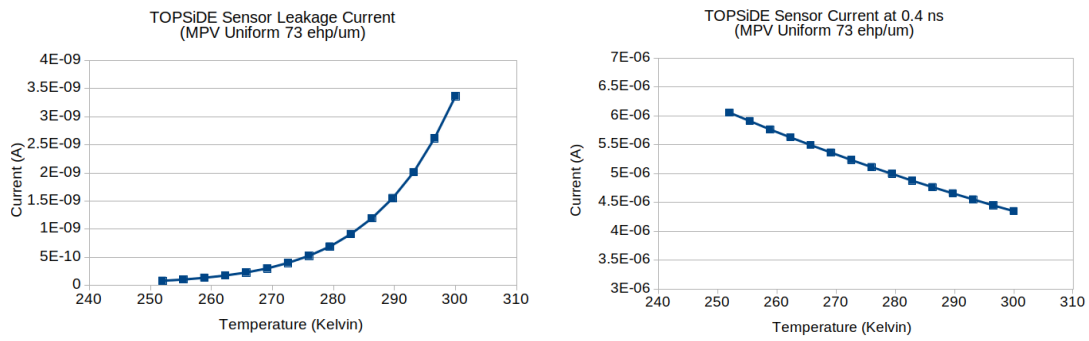
Figure 2. Temperature dependence of the a) leakage and b) signal current.
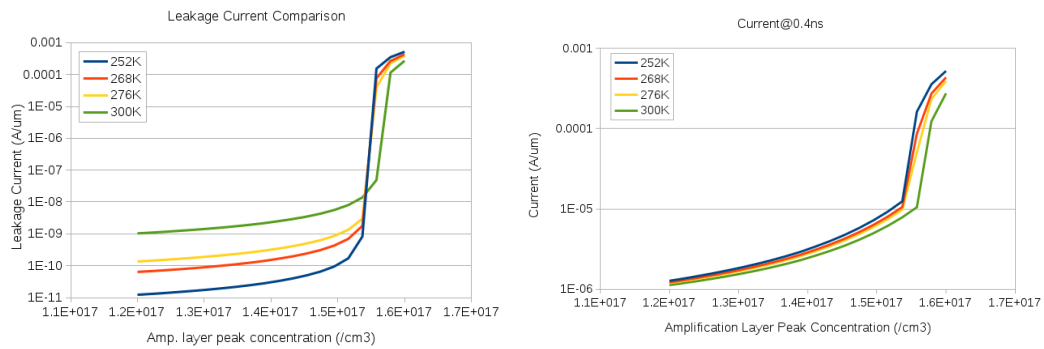

Figure 3. Dependence of the leakage current (left) and signal current (right) on the doping concentration. The different colored curves correspond to different operating temperatures.

As a further example, Fig. 3 left (right) shows the leakage (signal) current as function of doping concentration for different operating temperatures. It is found that independent of operating temperature, concentrations in excess of $1.5 \times 10^{17}/cm^3$ lead to unacceptably large leakage currents.

3. Staged development of integrated UFSDs

UFSDs with integrated digitization offer potentially two important advantages: a) the timing resolution will be further improved due to the elimination of transfer lines, and b) the production cost for large systems will be significantly reduced, due to the elimination of the need to produce a separate digitization system. At Argonne, we recently initiated work on implementing the readout circuitry onto the sensor. Figure 4 shows the schematic of the electronic readout system. The signal from the sensor are shaped, amplified and fed into a Constant-Fraction Discriminator (CFD). The precision arrival time of the signal is provided by the TOA time-to-digital converter (TDC), whereas the signal size is determined from the time-over-threshold (TOT) TDC. The serializer and LVDS circuitry will be located on the edge of the sensor.
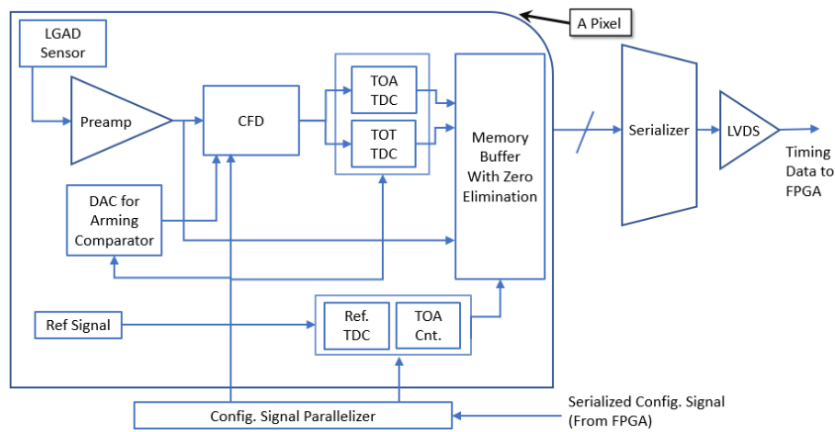
Figure 4. Schematic of the integrated readout circuitry. See text for details on the various components.

The implementation is being staged: In a first step the circuitry including the CFD is being prototyped with discrete components on a PCB board (named the CFD-board). The CFD-board has been fabricated and is being assembled at the time of this write-up. LGAD sensors (obtained from collaborating institutes) will be mounted on the CFD-boards and the signal will be collected by an FPGA-based data acquisition system, which includes the Time-to-Digital circuitry. Once a satisfactory performance will be achieved, the circuitry of the CFD-boards will be implemented onto each pixel in the sensor. These sensors with the 1st stages of the readout system implemented in each pixel, but still with a limited number of pixels, will be prototyped, to be followed by thorough tests.

After this 1st iteration, the complete readout system, including the time-to-digital converters and the serializer will be implemented onto the sensor. This step will again be followed by prototyping and testing. Finally, a sensor with the required, large channel count will be designed and produced.

4. Tests of UFSDs

Argonne initiated a test program for UFSDs. In a first step a complete test bench with a GigaHertz oscilloscope, power supplies, and an environmental chamber was assembled. In the subsequent months, additional testing equipment, such as a probe station, wire bonder, etc. will be acquired. In the meantime, we measured the IV and CV characteristics of various sensors with the tools graciously made available at Fermilab. Figure 5 left (right) shows a comparison of IV (CV) curves measured with a number of LGAD sensors and also a pin-diode. The sensors were obtained from different sources, like Brookhaven National Laboratory, FBK [6], and HPK [7]. The CV characteristics help to establish the range of operation from full depletion bias to breakdown voltage. Depending on the required gain, LGADs are typically operated near their breakdown voltage.
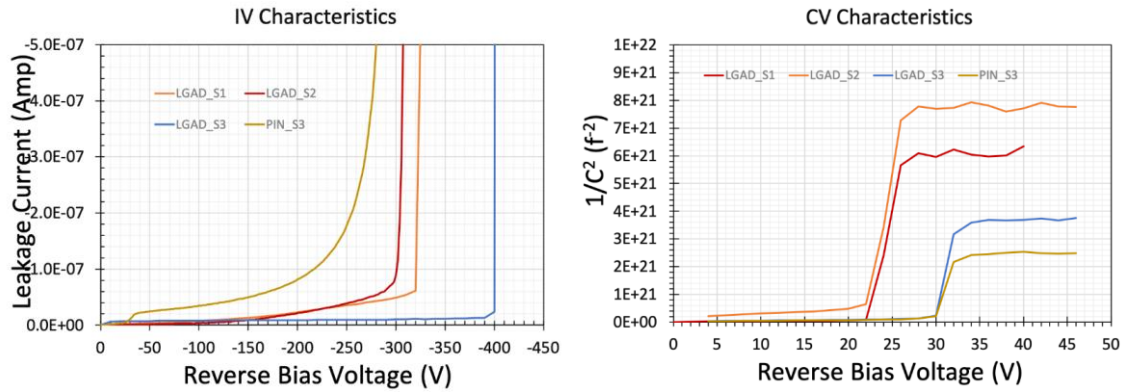
Figure 5. IV (left) and CV (right) characteristics as measured with various sensors and also a pin-diode.

In the last month, the Argonne group tested pairs of sensors in the Fermilab primary proton test beam [8]. The analysis of the data is still ongoing and will eventually establish the time resolution of these sensors.

5. Long-term plan: the PENTACAL

In the long-term, we plan to validate the concept of a particle-identifying, imaging calorimeter with the construction and testing of a small-scale electromagnetic calorimeter, dubbed the PENTACAL for obvious reasons. The prototype calorimeter features approximately 20 active layers interspersed with absorber plates. Each active layer contains a single 8 inch wafer with of the order of 32,000 1 x 1 mm^2 pixels, thus bringing the total number of channels for the PENTACAL close to 650,000. The absorber plates will be made of Tungsten (to preserve a short Molière radius), but will also include copper sheets to help maintain the envisaged operating temperature of -20 ^{0}C. Given the estimated power consumption of approximately 200 W/layer, Tungsten being a poor heat conductor can't serve as the only heat sink. The PENTACAL will be thoroughly tested in the Fermilab test beam and will serve as prototype for both the TOPSiDE electromagnetic calorimeter and the COMPASS++/AMBER [9] calorimeter upgrade. Comparison of the test results with GEANT4 based simulations will provide inside into the details of the time structure of electromagnetic and hadronic showers.

6. Summary

The planned Electron-Ion Collider, operating at a center-of-mass energy between 35 and 140 GeV is slated to start its physics program in the 2030s. The TOPSiDE detector concept aims at measuring and identifying each particle produced in the collisions individually, providing an output similar to the hadron level of Monte Carlo simulations. To achieve this, the concept takes

advantage of recent developments of technologies for colliding beam detectors, such as imaging calorimetry and Ultra-Fast Silicon Detectors. Going a step further, TOPSiDE combines imaging calorimetry and fast timing into a 5D calorimeter to provide particle identification as well, without the need of additional, separate systems located in front of the calorimeter.

A vigorous R&D program with the goal to establish integrated, pixelated silicon sensors with a time resolution of the order of 10 picosecond has been initiated at Argonne. At the time of this write-up, the design of the sensor is complete and the development of the readout circuitry is in progress. The design effort is being seconded with tests of sensors both on the bench and in particle beams.

References

[1] J. Repond*, Detector Concepts for the Electron-Ion Collider*, Proc. of 13th International Workshop on High p_T Physics in the RHIC and LHC Era (high-p_T2019), Knoxville, TN.

[2] J. Repond, *TOPSiDE: Concept of an EIC detector*, PoS DIS2018 (2018) 179.

[3] H. F. W. Sadrozinski et al., *4D tracking with ultra-fast silicon detectors*, Rept. Prog. Phys. **81** (2018), no.2, 026101.

[4] H. F. W. Sadrozinski, *Measurement of timing precision of ultra-fast silicon detectors*, talk given at the Workshop on 'Picosecond timing detectors for physics and medical applications', Torino, Italy (2018)..

[5] https://www.silvaco.com/products/tcad/device_simulation/atlas/atlas.html.

[6] https://iris.fbk.eu/

[7] https://www.hamamatsu.com/us/en/index.html

[8] https://ftbf.fnal.gov/

[9] https://nqf-m2.web.cern.ch/